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Potential for autumn aeration of stored rough rice and the potential number of generations of *Sitophilus zeamais* Motschulsky in milled rice in Japan ☆

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Abstract

Historical weather data from 84 sites in Japan were used to estimate the number of hours $\leqslant 15°C$ from 1 September to 31 October, based on the individual years from 1994 to1999, to evaluate the potential for using aeration at a threshold level of 15°C to cool rough rice stored during autumn. The number of hours $\leqslant 15°C$ in September and October ranged from 68 ± 21 in Kyushu to 1067 ± 27 h in northern Hokkaido. At an airflow rate of $0.0013\,m^3/s/m^3$, the time required to cool a storage silo containing rough rice to 15°C ranged from 85 days in southern Japan to 5 days in northern Japan. Weather data for the same sites were also used to estimate the number of hours below 15°C from 1 May to 30 September, to evaluate the potential of *Sitophilus zeamais* Motschulsky, the maize weevil, to infest bagged milled rice at ambient or uncontrolled temperatures. The number of hours $\leqslant 15°C$ from 1 May to 30 September ranged from 33 ± 15 h in Kyushu to 2392 ± 130 h on the northeastern coast of Hokkaido. As temperature decreased, there was a predicted increase in the number of days required to complete a generation, and as relative humidity increased, a predicted increase in the number of generations that could be produced. These simulation studies show how historical weather data can be used to develop risk management models for storage of bulk rough rice and bagged milled rice in Japan. Aeration during autumn could be used to cool large-bulk storage silos containing rough rice, while the simulations for development of *Sitophilus zeamais* populations on bagged milled rice emphasize the importance of insect management strategies for value-added products. Published by Elsevier Science Ltd.

Keywords: *Sitophilus zeamais*; Rice; Storage; Temperature; Aeration; Modeling

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1. Introduction

The use of low-volume ambient air to cool grain stored during autumn is an important component of management programs throughout many temperate regions (Armitage and Llewellin, 1987; Lasseran and Fleurat-Lessard, 1990; Thomas, 1990; Gardner et al., 1988; Cuperus et al., 1990). One widely used standard involves an airflow aeration rate of 0.0013 $m^3/s/m^3$ (0.1 ft^3/min/bushel, or CFM/bushel), for a total of 120 h while the ambient air is below a temperature threshold (for example, 15°C) to cool the grain mass to that temperature (McCune et al., 1963; Noyes et al., 1987). Simulation modeling studies using historical weather data have shown such controlled aeration is optimum for predicted population suppression of *Sitophilus zeamais* Motschulsky, the maize weevil, in maize stored throughout the eastern United States (Arthur et al., 1998, 2001). Simulation studies have also demonstrated that controlled aeration could be used to suppress populations of *Cryptolestes ferrugineus* (Stephens), the rusty grain beetle, in stored wheat in the United States (Flinn et al., 1997, Arthur and Flinn, 2000).

Rice is a major economic crop in Japan. It is harvested during autumn with exact harvest time depending on climate and variety, and stored as rough rice (paddy) either on-farm or in commercial facilities until it is milled. Bagged milled rice can be stored in large refrigerated climate-controlled warehouses, often as part of government sponsored programs, where the recommended temperature to prevent insect infestation is 15°C (Nakakita and Ikenaga, 1997). After the bagged milled rice is removed from these large storage facilities and moved into marketing channels where it is no longer refrigerated, it can become infested with insects, especially if it is stored at ambient conditions in small stores or storage sites. *S. zeamais* and *Sitophilus oryzae* (L.), the rice weevil, are important pests of stored rough rice and stored milled rice in Japan (Nakakita and Ikenaga, 1997). *S. zeamais* is found throughout Japan, while *S. oryzae* is more common in southern Japan (Kiritani, 1965).

Currently, aeration is not part of management programs for rough rice stored during autumn in Japan, and there are few published data from modeling studies or field trials describing the benefits or effects of aeration. In addition, there are no published studies that predict pest infestation levels during the summer in milled rice stored at ambient or uncontrolled temperatures. The objectives of this study were to: (1) use historical weather data to characterize temperature in Japan during late summer–early autumn (September and October), and during the warmer months from May through to the end of September; (2) combine weather data with simulated storage times to determine the potential of ambient aeration to cool stored rough rice during autumn in Japan; and (3) estimate the number of *S. zeamais* generations that could occur on bagged milled rice removed from cold storage and held at ambient conditions for different time periods during May to September, based on temperature profiles from the historical weather data.

2. Materials and methods

2.1. Autumn aeration and cooling of stored rough rice

Satellite temperature data for various sites in Japan were obtained from the web site of the US National Climatic Data Center (http://www.ncdc.noaa.gov). Data are available for several hundred sites in Japan. Sites, however, were eliminated if they were large population centers such as Tokyo and Kyoto, if they were above 1000 m in elevation, or if they were not on one of the four main islands of Hokkaido, Honshu, Shikoku, and Kyushu. Of the remaining sites, all those with more than 90 days of missing data for the 6-year period of 1994 through 1999 were eliminated, which left a total of 84 sites that were chosen for analysis. If any year for a particular site contained more than 61 days of missing data, that year was eliminated from analysis.

For each station, data sets for daily high and low temperatures were created for each year from 1994 to 1999. Data for missing values were added into the data sets for either high or low temperature by interpolating between the temperature before and after the missing date. If data were missing for two consecutive dates, the same procedure was followed to assign values for the missing dates. There were few occasions where data were missing for more than two consecutive dates. Yearly sets for daily sunrise and sunset times at each station were also obtained from the web site of the US Naval Observatory Astronomical Applications Department (http://aa.usno.navy.mil/AA/data).

To evaluate the potential for using aeration at a threshold level of 15°C to cool rough rice stored in Japan during autumn either on-farm or in commercial elevators, the total hours $\leqslant$15°C at each station during September and October for each year from 1994 to 1999 were estimated using a QBASIC program previously described in detail (Arthur and Johnson, 1995). Briefly, this program estimates the hourly temperature for any particular date using the high and low temperatures and the time of sunrise for that date, and the time of sunset from the previous date. Data at each station for each of the 6 years were then averaged using the Means Procedure of the Statistical Analysis System (SAS) (SAS Institute, 1987), and contour maps based on these average values were created using Surfer software (Golden Software, Golden Colorado, USA). Data from the plotted output in Surfer were used to create a map using Map Viewer software (Golden Software, Golden Colorado, USA), in which Japan was partitioned into climatic zones based on the average number of hours below 15°C during September and October for the years 1994–1999. These zones were as follows: zone 1, $<$100 h $\leqslant$15°C during September and October; zone 2, 101–200 h $\leqslant$15°C; and in similar increments of 100 h for zones 3–9 up to zone 10, which was $>$900 h $\leqslant$15°C (Fig. 2). Storage dates were estimated for each zone as 18 August, 25 August, 1 September, 8 September, 15 September, 22 September, 29 September, 6 October, 13 October, and 20 October for zones 1 through 10, respectively.

A calendar date at which rice would be harvested and stored at each station was estimated, using data for average harvest times for different rice varieties grown throughout Japan (Anonymous, 1992). In Kyushu and far southern Honshu, there can be two crops, one harvested in August and one in November, and the storage date chosen for these zones would represent the first crop in August. The average calendar dates at which rice could be put into storage in each zone were estimated as a mean of the dates for each station, and for each zone, a station was selected based on the approximate geographic mid-point of that zone. The calendar date by which stored rice could be cooled to 15°C in each year was estimated using the temperature data for the individual stations chosen to represent each zone. Starting with the binning date, the date at which 120 h $\leqslant$15°C were accumulated during each year at each station was calculated from the output data from the QBASIC program and averaged using SAS.

2.2. *Temperature profiles during summer and development of* S. zeamais

The potential for *S. zeamais* infestation during the warmer months of the year in bagged milled rice stored at ambient temperatures was estimated using the same temperature data sets for the 84 weather sites. In these simulations, the number of hours during each year from 1 May to 30 September that were $\leqslant 15°C$, which was taken as the developmental threshold for *S. zeamais*, were calculated for each station for each of the years from 1994 to 1999. The average values were then used to create a contour map in Surfer, which was re-drawn using Map Viewer, to partition Japan into climatic zones based on the temperature from 1 May to 30 September. These zones were in increments of 200 h as follows: zone 1, 0–200 h $\leqslant 15°C$; zone 2, 201–400 h $\leqslant 15°C$; and increasing in proportion up to zone 8. Zone 9 was 1601–1900 h $\leqslant 15°C$, and zone 10 was >1901 h $\leqslant 15°C$ (Fig. 3). For each zone, a station was selected based on both the approximate geographic mid-point of that zone and the actual hours $\leqslant 15°C$, similar to the procedures used to create the zones for temperature during 1 September to 31 October.

The potential for *S. zeamais* infestation in bagged milled rice at each station was estimated using a distributed-delay model based on the approximate developmental times of *S. zeamais* reared on maize at different temperatures (Throne, 1994). The equation used for predicting developmental time from egg to adult, $a + b/\mathrm{TEMP}^{0.5} + c\log_e(\mathrm{TEMP})/\mathrm{TEMP} + \mathrm{d}e^{-\mathrm{TEMP}} + f/\mathrm{r.h.}^2$, was a corrected form of the published equation (Throne, pers. comm.). Equation parameters *a*, *b*, *c*, *d*, *e*, and *f* were 5546.58, −103,275, 117,477, 2.91×10^8, 2.71828, and 81,979, respectively, TEMP is temperature in °C and r.h. is % relative humidity expressed as a whole number (60 for r.h. of 60%). This equation was chosen because it would predict generation times given different temperature and humidity conditions.

All dates in which the average temperature was $\leqslant 15°C$ were deleted, and the average daily temperature at each station from 1 May to 30 September, 1 June to 30 September, and 1 July to 30 September for each year was calculated and averaged using SAS. These temperature data sets were put into the developmental model, and simulations were run at 40%, 57%, and 75% r.h. to estimate developmental times, which were in turn used to predict the number of complete and partial generations of *S. zeamais* for these three different time periods at each of the sites within the zones.

3. Results

3.1. *Autumn aeration and cooling of stored rough rice*

Each of the 84 weather sites are listed alphabetically, along with the longitude, latitude, and elevation (Table 1) and plotted by approximate geographic location (Fig. 1). The yearly number of hours $\leqslant 15°C$ in September and October during each of the years from 1994 through 1999 ranged from a low of 68 ± 21 h at Nankishirahama airport (33°40′N, 135°21′E), on the eastern coast of Honshu to a high of 1067 ± 27 h at Omu (44°35′N, 142°58′E), on the northern coast of Hokkaido. Along with the normal cooling trends of moving from south to north, as shown by increased hours of temperature $\leqslant 15°C$, and similar trends moving upwards in altitude at the same latitude, there were some other geographic differences as well. In general, weather sites in western

Table 1
Longitude, latitude, and elevation of sites used for the temperature accumulation studies (approximate geographic location of each station shown by ID number in Fig. 1), and average yearly number of hours (±SEM of 6 years) ⩽15°C during autumn from 1 September to 31 October and in summer from 1 May to 30 September during each of the years from 1994 to 1999

ID no.	Station	Latitude (N)	Longitude (E)	Elevation (m)	Hours ⩽15°C 1 Sept.–31 Oct.	Hours ⩽15°C 1 May–30 Sept.
1	Abashiri	44°01′	144°17′	43	986±34	1880±116
2	Akita	39°43′	140°06′	21	560±50	986±87
3	Aomori	40°39′	140°46′	3	660±46	932±50
4	Asahikawa	43°46′	142°22′	116	989±37	1233±80
5	Atsugi	35°27′	139°27′	63	186±31	155±33
6	Chiba	35°36′	140°06′	19	198±24	199±30
7	Chofu	35°40′	139°32′	44	80±12	60±21
8	Choshi	35°44′	140°52′	28	98±22	227±44
9	Fukaura	40°39′	139°56′	67	661±49	923±47
10	Fukui airport	36°08′	136°14′	26	361±44	345±38
11	Fukushima	37°45′	140°27′	12	466±52	535±43
12	Fukuyama	34°27′	133°31′	3	342±45	310±52
13	Gifu	35°24′	136°46′	17	262±38	220±31
14	Hachinohe	40°32′	141°32′	28	654±43	1066±82
15	Hakodate airport	41°46′	140°49′	36	709±48	1304±79
16	Hamada	34°54′	132°04′	20	324±36	345±38
17	Hikone	35°16′	136°15′	89	324±46	337±45
18	Himeji	34°50′	133°40′	40	345±46	297±43
19	Hita	33°19′	130°56′	84	369±40	308±43
20	Hitoyoshi	32°13′	130°45′	147	339±41	294±46
21	Iida	35°31′	137°50′	484	516±58	520±57
22	Kagoshima	31°48′	130°43′	5	77±29	74±17
23	Kanazawa	36°33′	136°39′	28	314±49	329±31
24	Kawagughiko	35°30′	138°46′	861	719±72	943±71
25	Kitakyushu	33°50′	130°57′	6	96±17	33±15
26	Kochi airport	33°32′	133°40′	10	136±27	101±22
27	Kofu	35°40′	138°38′	24	348±49	264±42
28	Kumamoto	32°49′	130°43′	39	233±31	164±31
29	Kumagaya	36°09′	139°23′	319	301±37	278±33
30	Kushiro	43°02′	144°12′	98	939±49	1877±115
31	Kure	34°14′	132°23′	12	184±37	167±36
32	Maebashi	36°24′	139°40′	113	351±46	334±38
33	Maizuru	35°27′	135°19′	22	349±44	373±33
34	Matsue	35°27′	133°04′	22	344±41	323±32
35	Matsumato airport	36°10′	137°56′	660	626±58	634±62
36	Matsuyama airport	33°49′	132°42′	7	132±23	127±32
37	Mito	36°23′	140°28′	31	395±53	467±43
38	Miyako	39°39′	141°58′	47	632±44	1057±70
39	Miyazaki airport	31°52′	131°27′	9	167±32	112±27
40	Mombetsu	44°21′	143°22′	16	1003±33	1895±190
41	Morioka	39°42′	141°10′	157	716±51	936±49
42	Muroran	42°19′	140°59′	49	729±49	1432±61

(Continued on next page)

Table 1 (*continued*)

ID no.	Station	Latitude (N)	Longitude (E)	Elevation (m)	Hours $\leqslant 15°C$ 1 Sept.–31 Oct.	Hours $\leqslant 15°C$ 1 May–30 Sept.
43	Mutsu	41°17′	141°13′	5	756 ± 41	1229 ± 74
44	Nagano	36°40′	138°12′	419	547 ± 54	546 ± 55
45	Nagoya	35°10′	136°58′	56	249 ± 40	200 ± 30
46	Nankishirahama	33°40′	135°21′	108	68 ± 21	36 ± 13
47	Nara	34°41′	135°50′	106	362 ± 39	346 ± 38
48	Nemuro	43°20′	145°35′	26	1019 ± 53	2392 ± 130
49	Niigata	37°55′	139°09′	7	358 ± 41	375 ± 35
50	Obihiro	42°55′	143°31′	43	961 ± 36	1620 ± 106
51	Ofunato	39°04′	141°43′	37	573 ± 54	860 ± 56
52	Oita airpt.	33°29′	131°44′	8	125 ± 29	165 ± 28
53	Okayama airport	34°45′	133°35′	242	353 ± 39	301 ± 41
54	Omu	44°35′	142°58′	11	1067 ± 27	2208 ± 107
55	Onahama	36°57′	140°54′	5	350 ± 44	525 ± 46
56	Otaru	43°11′	141°01′	26	849 ± 39	1274 ± 54
57	Owase	34°04′	136°12′	27	226 ± 37	204 ± 36
58	Rumoi	43°57′	141°38′	28	964 ± 32	1498 ± 70
59	Saga	33°15′	130°18′	5	248 ± 26	186 ± 26
60	Sakata	38°54′	139°51′	4	484 ± 47	571 ± 54
61	Sasebo	33°09′	129°44′	15	178 ± 24	170 ± 31
62	Sendai	38°16′	140°54′	43	467 ± 51	652 ± 54
63	Shimonoseki	33°57′	130°56′	19	109 ± 20	109 ± 27
64	Shinjo	38°45′	140°19′	113	636 ± 58	791 ± 52
65	Shirakawa	37°07′	140°13′	356	604 ± 61	784 ± 56
66	Shizuoka	34°58′	138°24′	15	186 ± 41	179 ± 29
67	Takada	37°06′	138°15′	18	415 ± 48	462 ± 42
68	Takayama	36°09′	137°15′	561	605 ± 62	679 ± 68
69	Takamatsu airport	34°13′	134°01′	188	285 ± 35	230 ± 35
70	Tateyama	34°59′	139°50′	6	126 ± 21	136 ± 31
71	Tokushima	34°08′	134°37′	11	138 ± 33	97 ± 20
72	Tottori airport	35°23′	134°10′	18	270 ± 30	222 ± 43
73	Toyama airport	36°39′	137°11′	27	322 ± 39	286 ± 29
74	Tsu	34°44′	136°31′	18	202 ± 34	173 ± 34
75	Tsuruga	35°29′	136°04′	12	275 ± 35	306 ± 41
76	Tsuyama	35°04′	134°01′	147	468 ± 56	461 ± 55
77	Urakawa	42°10′	142°47′	37	835 ± 50	1734 ± 100
78	Utsunomiya	36°33′	139°52′	140	375 ± 51	402 ± 44
79	Uwajima	33°14′	132°33′	44	205 ± 34	189 ± 34
80	Wajima	37°23′	136°54′	14	434 ± 51	533 ± 44
81	Wakamatsu	37°29′	139°55′	213	565 ± 58	606 ± 54
82	Wakeyama	34°14′	135°10′	18	177 ± 26	131 ± 28
83	Yamagata	38°15′	140°21′	153	573 ± 58	631 ± 49
84	Yamaguchi	33°56′	131°17′	8	203 ± 28	117 ± 27

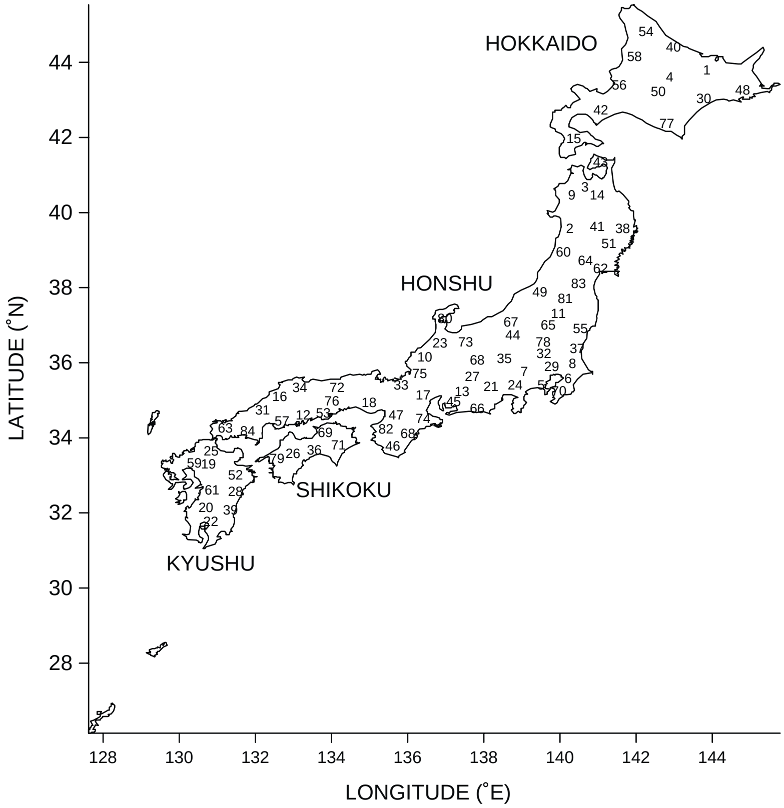

Fig. 1. Approximate geographic location of the 84 weather sites used in the study, as listed alphabetically in Table 1, the numbers on the figure correspond to numbers on the list.

Japan appeared to be cooler than stations at the same or similar latitudes in eastern Japan. For example, the number of hours $\leqslant 15°C$ at Tottori (35°23′N, 134°10′E) and Tateyama, (34°59′N, 139°50′E), two stations at similar latitudes and elevation, were 270 ± 30 and 126 ± 21, respectively. Similar comparisons can be made for many other locations as well. In addition, temperatures seemed to become progressively cooler at those locations above 38°N, compared with a less rapid decrease in temperature from weather sites located from 32°N to 38°N.

The stations representing the various autumn climatic zones are given in Table 2, and the locations are shown by the corresponding number in Fig. 2. The estimated binning date for stored rough rice, the date by which 120 h $\leqslant 15°C$ are accumulated, and the number of days required to cool stored rough rice to 15°C are estimated for each of the stations chosen to represent the 10 climatic zones (Table 2, Fig. 2). The impact of later harvesting and storage dates with northward progression of the climatic zones, combined with cooler temperatures, is seen by comparing the number of days required to cool rough rice stored in each zone. This impact is especially noticeable in the northern zones. In zone 1, represented by Kagoshima (31°48′N, 130°43′E), 85 days are required to accumulate 120 h $\leqslant 15°C$, while in zone 5, represented by Fukushima, (37°45′N, 140°27′E), 25 days are required to accumulate the 120 h. The difference in terms of the

Table 2
Stations chosen to represent climatic zones for rough rice stored in Japan and the simulated date rice would be stored. The average date rice would be stored (calendar date and Julian date) and the date (mean ± SEM, calendar date and Julian date) by which 120 h ≤15°C would be accumulated at each site, based on temperature data from 1994 to 1999, was determined by starting the accumulations from the specific storage date for each station and zone

Zone	Station	Storage date of rough rice	Date when 120 h ≤15°C are accumulated	Days needed for cooling
1	Kagoshima	18 (230) Aug.	11 (315) Nov. ± 3.3	85
2	Tokushima	25 (237) Aug.	30 (303) Oct. ± 3.5	66
3	Owase	1 (244) Sept.	22 (295) Oct. ± 3.0	51
4	Fukui	8 (251) Sept.	14 (287) Oct. ± 3.1	36
5	Fukushima	15 (258) Sept.	10 (283) Oct. ± 3.3	25
6	Akita	22 (265) Sept.	8 (281) Oct. ± 1.6	16
7	Fukaura	29 (272) Sept.	9 (282) Oct. ± 0.7	10
8	Mutsu	6 (279) Oct.	13 (286) Oct. ± 0.3	7
9	Otaru	13 (286) Oct.	19 (292) Oct. ± 0.4	6
10	Mombetsu	20 (293) Oct.	26 (299) Oct. ± 0.2	5

days required to cool rough rice stored in zone 5 compared with zone 1 is 60 days. In contrast, the difference between the time required to cool rough rice in zone 10, represented by Mombetsu, (44°21′N, 143°22′E) and zone 5 is only 20 days. Similar comparisons can be made for other climatic zones shown in Table 2 and Fig. 2.

3.2. Temperature profiles during summer and development of S. zeamais

The number of hours ≤15°C from 1 May to 30 September during each of the years from 1994 through 1999 ranged from a low of 33 ± 15 h at Kitakyushu (33°50′N, 130°57′E), on the western coast of Kyushu to a high of 2392 ± 130 h at Nemuro (43°20′N, 145°35′E) (Table 1), on the northeastern coast of Hokkaido. Cooling trends during this period of 1 May to 30 September were evident with northward progression in latitude and upward progressions in altitude, similar to results for hours of temperature accumulations ≤15°C during 1 September–31 October. However, temperatures during 1 May–30 September at sites in western Honshu were usually more comparable to those sites at similar latitudes and elevations in eastern Honshu, in contrast to the results for the temperature accumulations from 1 September to 31 October. Above approximately 35°N, temperatures became progressively cooler, and temperatures were slightly warmer on the western side of Honshu compared to the east. At locations above 38°N, the climate during 1 May–30 September cooled dramatically, compared with the less rapid decrease in temperature from weather sites located from 32°N to 38°N, similar to what was observed for temperature patterns during September and October.

The stations chosen to represent summer temperature in each zone are given in Table 3, and the locations are shown by the corresponding number in Fig. 3. The difference between the temperature profiles of 1 May–30 September and 1 September–31 October is also seen in the placement for Fukushima (37°45′N, 140°27′E). This site represents zone 5 in Fig. 2 and zone 3 in Fig. 3, indicating that the temperature contrasts between northern and southern Honshu were

Fig. 2. Average number of hours (±SEM of 6 years) ⩽15° C during 1 September–31 October, for 10 climatic zones created from the data set in Table 1: zone 1, <100 h ⩽15°C; zone 2, 101–200 h ⩽15°C; and in similar increments of 100 h for zones 3–9 up to zone 10 which was >901 h ⩽15°C (Fig. 2). One station was chosen to represent each zone (Table 2), and the locations are shown by the corresponding number in Fig. 2.

much greater from 1 September to 31 October compared with 1 May through 30 September. The total numbers of days from 1 May to 30 September, 1 June to 30 September, and 1 July to 30 September are 153, 122, and 92, respectively. The average number of days (± SEM) in which the average daily temperature was >15°C from 1 May, 1 June, and 1 July to 30 September in each year from 1994 to 1999, and the average temperature during those time periods (mean±SEM), is shown for each weather site representing the 10 climatic zones (Table 3).

In general, as the weather sites are located from south to north, there are fewer days in each time period in which the average temperature is >15°C, and the average temperature for the days in which the developmental threshold is exceeded decreases with the northward progression of the weather sites. In addition, the percentage of days at each station that exceed the developmental threshold (the average number divided each by the total number of days) increases during 1 June to 30 September compared with 1 May to 30 September, then increases again from 1 July to 30 September. As an example, the percentage of days at Himeji (34°50′N, 133°40′E) that exceed the

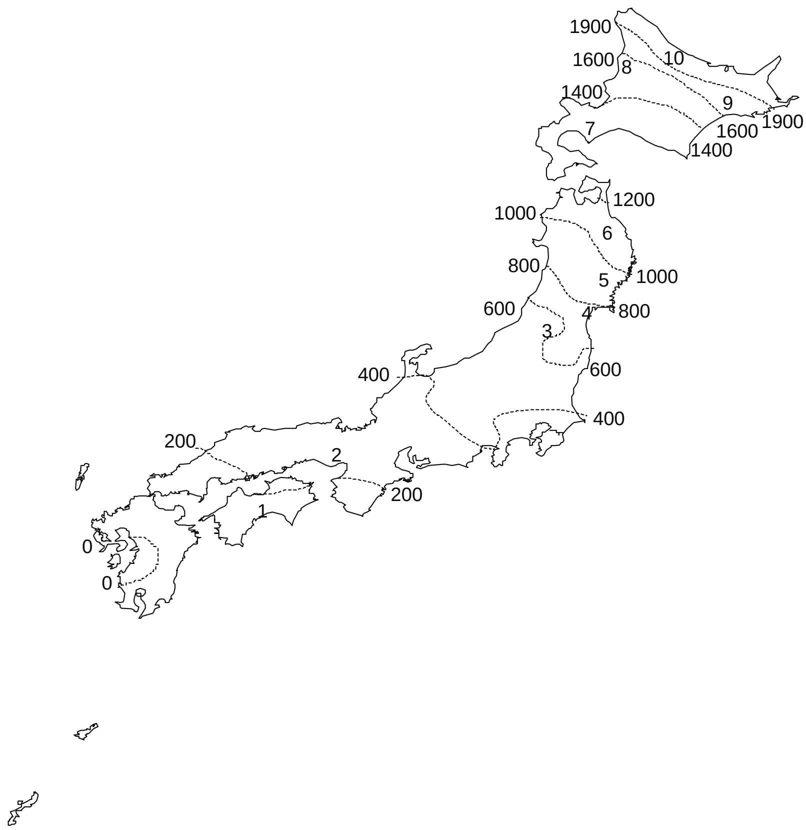

Fig. 3. Average number of hours ($\pm$SEM of 6 years) $\leqslant 15°$ C during 1 May–30 September, for 10 climatic zones created from the data set in Table 1: These zones were in increments of 200 h as follows: zone 1, 0–200 h $\leqslant 15°$C; zone 2, 201–400 h; and increasing in similar increments of 200 h up to zone 8. Zone 9 was 1601–1900 h $\leqslant 15°$C, and zone 10 was >1901 h $\leqslant 15°$C (Fig. 3). One station was chosen to represent each zone (Table 3), and the locations are shown by the corresponding number in Fig. 3.

developmental threshold from 1 May, 1 June, and 1 July to 30 September is 97.3, 100, and 100, respectively, while the percentage of days at Hachinohe (40°32′N, 141°32′E) exceeding the threshold during these time periods is 69.1, 85.4, and 95.5, respectively (Table 3).

The percentage of days exceeding the threshold generally decreases with the northward progression of the stations; however, temperatures throughout most of Honshu become more uniform as the summer progresses. The percentage of days exceeding the threshold from 1 July to 30 September at stations 1–6 in Honshu range from 95.5% to 100%, while the corresponding range for the percentage of days exceeding the threshold at those stations during 1 May–30 September and 1 June–30 September is 69.1–99.6% and 85.4–100%, respectively. At each station, the average temperature for the days exceeding the threshold increases slightly from 1 June to 30 September in comparison with 1 May to 30 September, and also from 1 July to 30 September as compared with 1 June to 30 September, partly because of the warmer temperatures during July and August. Also, this average temperature increases because of the fact that the days in May and

Table 3
Stations chosen to represent climatic zones for bagged milled rice stored in Japan from 1 May to 30 September (number corresponds to location shown in Fig. 3)

Zone	Station	1 May–30 Sept.		1 Jun.–30 Sept.		1 Jul.–30 Sept.	
		Number of days	Temperature	Number of days	Temperature	Number of days	Temperature
1	Kochi	152.5±0.3	24.6±0.1	122.0±0.0	25.7±0.1	92.0±0.0	26.5±0.1
2	Himeji	149.0±1.4	23.4±0.1	122.0±0.0	25.0±0.1	92.0±0.0	26.0±0.2
3	Fukushima	140.3±1.4	22.5±0.2	118.3±1.4	23.2±0.2	90.7±1.1	24.1±0.2
4	Sendai	133.2±2.5	21.6±0.1	117.2±1.2	22.1±0.2	91.5±0.5	22.9±0.2
5	Morioka	123.0±3.2	21.1±0.2	113.2±1.9	21.4±0.2	88.2±1.4	22.2±0.2
6	Hachinoe	114.2±4.0	20.7±0.1	104.2±2.7	21.0±0.2	87.8±1.0	21.5±0.2
7	Hakodate	105.5±3.4	20.1±0.1	103.3±3.1	20.2±0.1	89.8±0.8	20.6±0.2
8	Rumoi	94.7±3.6	19.6±0.2	92.0±3.3	19.6±0.2	81.0±2.0	19.9±0.2
9	Kushiro	80.7±5.0	18.9±0.2	78.0±4.5	18.9±0.2	72.0±4.3	19.1±0.2
10	Omu	64.2±4.2	18.8±0.2	61.5±4.3	18.8±0.3	57.3±3.7	18.9±0.3

Number of days (mean ± SEM of 6 years) whereby the average daily temperature exceeded the developmental threshold of 15°C at each station from 1 May, 1 June, and 1 July to 30 September, based on yearly data from 1994 to 1999, and the average daily temperature (± SEM of 6 years) for the days in which the threshold was exceeded.

June in which the recorded daily average temperature was $\leqslant$15°C have been removed from the data sets, and were not used in the calculations to determine average temperatures for the entire time period.

These temperature differences among the 10 weather stations and the three different time periods are also reflected in the predicted times required to complete a *S. zeamais* generation and the predicted number of generations at each station during each respective time period (Table 4). The average temperatures (Table 3) were used to predict the number of days required to complete a generation at 40%, 57%, and 75% r.h., which was divided into the number of days on which that average is based (also from Table 3), to estimate the predicted number of generations that could occur at those specific temperature–humidity conditions. At each station, there is a decrease in the number of days required to complete a generation, and a corresponding increase in the predicted number of generations, with each successive increase in relative humidity. There is also a slight decrease in the number of days required to complete the generation from 1 May to 30 September compared with 1 June and 1 July to 30 September, which is a reflection of the slight increase in the average temperature for each of those time sequences. The relative humidity has a significant impact on the predicted number of generations from the northernmost to the southernmost stations; at 40% r.h., the range between Omu and Kochi with respect to the number of generations predicted for 1 May–30 September is 0.6–2.2, while at 57% and 75% r.h. the range increases to 0.9–3.4 and 0.8–4.5 generations, respectively. A similar pattern of an increased number of generations predicted for the different stations and zones moving from north to south, and a greater range in the number of generations predicted for Omu, the coolest site, and Kochi, the warmest site, are also evident at the other two time periods. These patterns are also a reflection of the warmer temperatures during 1 May–30 September throughout most of Honshu, as compared to the cooler temperatures found on Hokkaido.

Table 4
The number of *Sitophilus zeamais* generations, as determined by the model described by Throne (1994), predicted to occur in bagged milled rice stored at ambient temperature, 40%, 57%, and 75% r.h., during 1 May–30 September, 1 June–30 September, and 1 July–30 September at each station and climatic zone[a]

Zone	Station	40% r.h.		57% r.h.		75% r.h.	
		Days	Generations	Days	Generations	Days	Generations
1 May–30 Sept.							
1	Kochi	70.2	2.2	44.7	3.4	33.6	4.5
2	Himeji	73.6	2.0	47.6	3.1	36.9	4.0
3	Fukushima	81.8	1.7	55.8	2.5	45.2	3.1
4	Sendai	88.2	1.5	62.2	2.1	51.5	2.6
5	Morioka	92.1	1.3	66.1	1.9	55.4	2.2
6	Hachinoe	95.3	1.2	69.3	1.6	58.7	1.9
7	Hakodate	100.5	1.0	74.5	1.4	63.7	1.7
8	Rumoi	105.0	0.9	79.0	1.2	68.3	1.4
9	Kushiro	111.5	0.7	85.5	0.9	74.8	1.1
10	Omu	112.4	0.6	86.4	0.9	75.8	0.8
1 June–30 Sept.							
1	Kochi	66.1	1.8	40.0	3.1	29.4	4.1
2	Himeji	69.4	1.7	43.4	2.8	31.9	3.8
3	Fukushima	78.6	1.5	52.6	2.2	40.8	2.9
4	Sendai	86.0	1.4	60.0	1.9	47.9	2.4
5	Morioka	91.3	1.2	65.3	1.7	53.1	2.1
6	Hachinoe	94.5	1.1	68.5	1.5	56.2	1.8
7	Hakodate	101.4	1.0	75.4	1.4	62.9	1.6
8	Rumoi	106.8	0.9	80.8	1.1	68.3	1.3
9	Kushiro	113.4	0.7	87.4	0.9	74.8	1.0
10	Omu	114.3	0.5	88.3	0.7	76.7	0.8
1 July–30 Sept.							
1	Kochi	64.3	1.4	38.3	2.4	27.1	3.4
2	Himeji	65.7	1.4	39.7	2.3	28.5	3.2
3	Fukushima	73.6	1.2	47.6	1.9	35.9	2.5
4	Sendai	80.5	1.1	54.5	1.7	42.6	2.1
5	Morioka	85.3	1.0	59.3	1.5	47.2	1.9
6	Hachinoe	90.5	0.9	64.5	1.4	52.3	1.7
7	Hakodate	97.9	0.9	71.9	1.2	59.5	1.5
8	Rumoi	104.1	0.8	78.1	1.0	65.6	1.2
9	Kushiro	111.5	0.6	85.5	0.8	72.4	1.0
10	Omu	113.4	0.5	87.4	0.6	74.8	0.8

[a] The number of days required to complete a generation during each time period at each weather site was determined by inputting the calculated average temperature during each of the three time periods, using only those days when average daily temperature was $>15°C$ (from Table 3), for each relative humidity (% r.h.). The number of days at the average temperature (from Table 3) was divided by the number of days required to complete a generation at each temperature–relative humidity combination to determine the number of generations.

4. Discussion

Stored bulk grains have a low heat capacity and low thermal conductivity, which means that heat transfer is a slow process under conditions of natural cooling (Multon, 1988). Below the first meter of the surface layer, temperatures inside the bulk grain mass will lag behind ambient temperatures, and the grain will cool gradually during autumn in response to decreasing temperatures (Longstaff and Banks, 1987). As a result of these thermodynamic cooling processes, large temperature differentials can exist between the cool surface and the comparatively warmer bulk grain mass (Foster and Tuite, 1982). These temperature patterns in stored grain can be described by simulation models; one of the more recent ones was published for wheat stored in Beijing, China (Jia et al., 2001). Model inputs were an initial grain storage temperature of 22°C and starting storage date of 1 June. Model predictions showed that near the grain surface, temperatures would drop to 15°C after 210 days of storage, while the temperature near the center of the grain mass would not reach this level until 290 days. However, the actual ambient temperature dropped to 15°C after 120 days of storage. The results of this simulation model show the insulating properties of bulk grain, and how minimum temperatures within the grain mass are usually far above the minimum ambient temperatures for similar time periods.

Many published field studies, summarized by Reed and Arthur (2000), have shown the benefits of aeration for reducing insect populations in stored grain. Several simulation studies have also been published whereby engineering models have been combined with weather data to predict temperatures profiles, and the resulting insect population development, within the bulk grain mass inside cylindrical upright storage structures (Maier et al., 1996; Flinn et al.,1997; Arthur et al., 1998; Arthur and Flinn, 2000; Arthur et al., 2001). The model described by Maier et al. (1996) divides the grain mass into the peripheral and bulk regions, which comprise 10% and 90% of the grain mass, respectively, while the model described by Flinn et al. (1997) compartmentalizes the grain mass into different sections. In the current study, an aeration airflow rate of $0.0013\,m^3/s/m^3$ was specified for the model simulations because it is a standard recommendation for stored grains in the United States (Noyes et al., 1987) and other temperate regions (Reed and Arthur, 2000). In previous model simulation studies with *S. zeamais*, increasing the airflow rate to 0.0026 and $0.0039\,m^3/s/m^3$ led to a predicted decrease in the time required to cool stored corn, but had little predicted impact on predicted populations of *S. zeamais* (Arthur et al., 1998). In addition, 15°C was shown to be the optimum temperature for cooling and for population suppression (Arthur et al., 1998).

When using autumn aeration, these models usually predict that it takes anywhere from 2 weeks to 3 months to cool grain to 15°C, depending on the climate and the initial grain temperature. In unaerated bins stored at the same locations, there is a further delay of at least 2–3 months before temperatures in the bulk mass drop to 15°C. In addition, without aeration the temperature in the bulk mass may not even reach this threshold of 15°C in sub-tropical or warm temperate climates, such as the southern United States (Arthur et al., 1998; Arthur and Flinn, 2000). Simulations for insect development, utilizing the predicted grain temperatures, show a large difference in the predicted population levels that could occur in autumn in unaerated grain as compared with predicted populations in aerated grain. One limitation of using simulation models to predict temperatures within the grain mass is that these models are often very complex and require hourly weather data, which are available for only a few limited geographic locations within a specific country.

Differences in temperature between the surface and the bulk grain mass can also lead to problems with moisture migration from natural internal convective cooling, which will increase the potential for mold and fungal development (Jia et al., 2001). Moisture migration can also occur even when grain is dry because of high initial storage temperatures (Metzger and Muir, 1983). Aeration with low-volume ambient air is a standard recommendation for cooling stored grain to equalize the temperature within the storage environment, thereby reducing the potential for insect pest development and ensuring quality preservation during storage (Reed and Arthur, 2000).

The current system for managing rough rice in Japan includes both on-farm storage in small sites and storage in large elevator silos. The elevator storages are distributed throughout the country, and are utilized to hold the rice until it can be milled and bagged. Rough rice or paddy rice can become infested with stored product insects, including *S. zeamais* and *S. oryzae* (Samson and Parker, 1989; Samson et al., 1989). *S. zeamais* occurs throughout Japan while *S. oryzae* is distributed mainly in southern Japan, and *S. zeamais* is considered to be the more cold-tolerant species (Nakakita and Ikenaga, 1997). A unique behavior has been ascribed to *S. zeamais* in Japan in that it migrates from farm and mill storage sites during autumn, over-winters in the outside environment, and returns in the spring (Kiritani, 1965; Nakakita and Ikenaga,1997). Both of these papers cite a publication by Takahashi (1931, in Japanese) as the original source and description of this migratory behavior of *S. zeamais*. However, the behavior of *S. zeamais* may vary in large modern elevators storing bulk rough rice, because the temperature patterns would be much different from those in small bulk storages or in mills containing bagged rice. If *S. zeamais* tend to remain in the bin in these modern large-bulk storage sites, aeration could be utilized to reduce bulk temperatures to the threshold development level of 15°C.

The results for the simulation studies described in this paper for September and October show how quickly rough rice stored in different regions within Japan could be cooled to threshold levels of 15°C, using low-volume ambient aeration. In southern Japan, aeration could have potential benefits because the bulk grain mass would be cooled much faster than the rate which could be accomplished under natural conditions. Autumn populations could be reduced, which would also impact the potential population growth that could occur in the spring. In regions where initial grain temperatures are over 30°C, aerating and cooling to levels of 22–24°C would limit insect population development. This strategy is being advocated for wheat stored during the summer in the United States (Flinn et al., 1997; Reed and Harner, 1998a, b; Arthur and Flinn, 2000). In more northern regions, the bulk grain mass would reflect the temperature at the time rice was put into the bin, which could be well above the developmental threshold of 15°C. Aeration in these northern areas would quickly cool the entire grain mass, as shown by the results in Table 2 for northern Honshu and Hokkaido, and equalize temperatures throughout the bulk mass.

The impact of temperature and relative humidity on the production of *S. zeamais* in bagged milled rice is seen in the second set of simulations, in which the potential number of generations were predicted for bagged milled rice held at ambient temperatures for one of three time periods, 1 May, 1 June, or 1 July to 30 September. Such a situation could exist when bagged rice is removed from storage at 15°C and put inside secondary storage warehouses, small retail groceries, food warehouses, or urban homes and held without temperature controls. Developmental rates of

S. zeamais and *S. oryzae* vary slightly with species and commodity. Kiritani (1965) cites studies in Japan where *S. zeamais* developed faster than *S. oryzae* when reared on rice, and cites studies from Birch (1944, 1953) where *S. oryzae* developed faster than *S. zeamais* when reared on wheat, but the reverse was true when both were reared on maize and rice. He also cites unpublished data which give the developmental times of *S. zeamais* and *S. oryzae* strains collected from Japan as 24.01 and 26.56 days, respectively, on rice and 27.12 and 28.66 days, respectively, on maize at 30°C, 70–80% r.h. However, these differences between the two species and the two commodities vary by only 2–3 days.

Ryoo and Cho (1988) published a model for development of *S. oryzae* on polished rice at temperatures of 20–33°C. These studies, however, were conducted only at a moisture content of 14.5%, which is about 75% r.h. (Greenspan, 1977). This and other published studies for development of *S. zeamais* or *S. oryzae* on rice (Nakakita and Ikenaga, 1997) focused more on maximum rates of production and intrinsic growth rates and did not give an equation for predicting generation times of either species. In the current study, the model by Throne (1994) was used to predict the number of *S. zeamais* generations that could develop in bagged rice because it was based on a comprehensive set of observations at different temperatures and relative humidities, rather than a single set of conditions. The relative order, and the magnitude of changes between the stations chosen to represent the 10 climatic zones would be similar for *S. zeamais* and *S. oryzae* regardless of species or commodity.

In most countries in the temperate regions of the northern hemisphere, there are less temperature contrasts along north–south gradients during the summer months compared with the autumn and winter months. This was seen in the results for the simulation studies for 1 May–30 September, in which the temperatures throughout most of the island of Honshu were less variable compared with temperatures from 1 September to 31 October. This relative homogeneity over a broad geographic range shows how rapidly *S. zeamais* populations can develop in bagged rice during the summer if it is not stored in climate-controlled conditions, and emphasizes the necessity of storing bagged milled rice at 15°C or lower to prevent infestations of *S. zeamais.*

In other temperate countries which produce rice, the rice is stored primarily as rough rice in bulk silos, and after milling is distributed in the various marketing channels. In Japan, there is considerable storage of milled rice, which is a value-added product compared with rough rice. Therefore, it may be necessary to emphasize continued protection of milled rice throughout the distribution system in Japan, before it reaches retail stores and is purchased by consumers. Stored-product insects such as *S. zeamais* can cause considerable damage in food products, and the source of the infestation can be within the store or warehouse or come from infested product that has been brought into the store (Arbogast et al., 2000). If milled rice is infested with an internal feeder like *S. zeamais*, the infestation could continue to develop after the product is purchased by consumers, and the adults could emerge from the kernel and contaminate other products in the home. Long-term storage of milled rice in private homes should be done under climatically controlled conditions to prevent infestations from arising and spreading.

These simulation studies show how historical weather data can be used to develop management models for raw bulk grains and finished products stored within a large geographic area or specific country, as has been done here for Japan. Specific insect pest management strategies can be developed for different regions, depending on the availability and economic feasibility of control options. For example, it may be possible to concentrate some storage structures and systems in cooler regions where ambient temperatures can be utilized to help maintain storage temperatures below developmental thresholds, such as 15°C. Models utilizing historical weather data may be easier to develop in the future because of the availability of temperature and other climatic data from web-based information sites. All of the temperature data used in our study was obtained from web sites maintained by the United States National Oceanographic and Aeronautic Administration (NOAA) and the US Naval Observatory.

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